

Vector Dark Matter Detection using the Quantum Jump of Atoms

Qiaoli Yang*

*MOE Key Laboratory of Fundamental Physical Quantities Measurements,
Department of Physics, Huazhong Univ. of Science and Technology, Wuhan, 430074.*

Haoran Di

Department of Physics, Huazhong Univ. of Science and Technology, Wuhan, 430074.

(Dated: June 28, 2016)

Abstract

The hidden sector $U(1)$ vector bosons created from inflationary fluctuations can be a substantial fraction of dark matter if their mass is around 10^{-5}eV . Due to the creation mechanism, the dark matter vector bosons are a condensate with a very small velocity dispersion, which makes their energy spectral density $\rho_{\text{cdm}}/\Delta E$ very high. Therefore, the dark electric dipole transition rate in atoms or ions is boosted if the energy gap between atomic states equals the mass of the vector bosons. By using the Zeeman effect, the energy gap between the 2S state and the 2P state in hydrogen atoms or hydrogen like ions can be fully tuned and the $2S_{1/2}$, $m_j = -1/2$ state can be made a semistable ground state. The 2S state can be populated with electrons due to its relatively long life, which is about 1/7s. When the energy gap between the semi-ground 2S state and the 2P state matches the mass of the cosmic vector bosons, induced transitions occur and the 2P state subsequently decays into the 1S state. The $2P \rightarrow 1S$ decay emitted photons can then be registered. The choices of target atoms depend on the experimental facilities and the mass ranges of the vector bosons. Because the mass of the vector boson is connected to the inflation scale, our experiment may provide a probe to inflation.

* qiaoli_yang@hotmail.com

I. INTRODUCTION

The existence of dark matter has been widely accepted due to the discovery of ample evidence such as the observations of the cosmic microwave background anisotropy, gravitational lensing and galactic rotational curves. The properties of dark matter particles include that they are non-baryonic, weakly interacting and stable. There are many theories that can provide a proper dark matter candidate and these dark matter candidates can be categorized into two major classes: 1, axions/axion like particles (ALPs) [3–6, 10, 11] created by the misalignment mechanism and massive vector dark bosons [9, 12, 25] created from inflationary fluctuations; and 2, weakly interacting massive particles (WIMPs) [17, 18] created from the thermal production in hot plasma. The axions/ALPs and the vector dark matter are bosons with a typically smaller mass (sub eV) and higher phase space density, which makes them behave more like waves or condensate. The WIMPs are much heavier ($>\text{GeV}$) and have a thermal distribution so they behave more like particles. Experiments searching for these dark matter candidates are currently proceeding or in planning in laboratories around world [14, 15, 20–23].

The hidden massive $U(1)$ vector boson [12], dark photons, can be a substantial fraction of dark matter. The cosmic dark photon populations are generally non-thermally created by the misalignment mechanism [16] and/or from inflationary fluctuations [8, 9, 16, 25]. The recently discovered inflationary fluctuation creation [25] is very appealing because it connects the dark matter mass with the Hubble scale of inflation. It is found that although the well known scalars and tensors power spectra created from the inflation fluctuations are scale invariant, the vector power spectrum peaks at intermediate wave length. Therefore, long-wavelength, isocurvature perturbations are suppressed so the production is consistent with the cosmic microwave background anisotropy observations. The mass of the dark photons is $10^{-5}\text{eV}(10^{14}\text{GeV}/H_I)^4$ provided that the dark photons account for most of the dark matter energy density, where H_I is the Hubble scale of inflation.

The number density N of sub eV dark photons is currently very high, of the order of $N = \rho_{cdm}/M \gtrsim 3 * 10^8 \text{ cm}^3$, where ρ_{cdm} is the dark matter energy density. Therefore we can treat the cosmic dark photons as a classical field. The dark photon field is mostly composed by the dark electric field $|\vec{E}'_0| \approx \sqrt{2\rho_{cdm}}$, as we show in the next section, thus the dark magnetic field is negligible. In addition, the cosmic dark photons have a very high

phase space density because their velocity dispersion is of the order of $\delta v \sim v \sim 10^{-3}c$. Thus the electric dipole transition induced by the dark photons in an atom is enhanced. This makes the quantum transitions of atoms or ions a suitable method for detecting cosmic dark photons.

Many proposed and current experimental studies are looking for cosmic dark photons [13, 19, 23, 24, 26, 27]. The proposed and current experiments include electromagnetic resonator experiments (such as the ADMX), LC oscillator experiments, Xenon10, and the newly proposed absorption of dark matter by a superconductor. Each experiment suits a different mass range. The proposed study presented here is suitable for $M \lesssim 2 * 10^{-4}\text{eV}$ with a higher sensitivity when the mass is smaller, see Figure 2.

II. VECTOR DARK MATTER

The hidden $U(1)$ vector boson has a small mass and a very weak coupling to the standard model photon. Let us use A'_μ to denote the new vector field, the effective Lagrangian therefore can be written as:

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4}(F^{\mu\nu}F_{\mu\nu} + F'^{\mu\nu}F'_{\mu\nu} + 2\chi F'^{\mu\nu}F_{\mu\nu}) \\ & - \frac{M^2}{2}A'_\mu A'^\mu - e\bar{\psi}\gamma^\mu\psi A_\mu + \dots, \end{aligned} \quad (1)$$

where $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$, χ is the mixing parameter, M is the mass of the hidden $U(1)$ boson, and ψ are fermions with ordinary electric charge in the standard model sector. The mixing term results in oscillations between the two $U(1)$ bosons. We can redefine the field to mass eigenstates to get a massive vector boson and a massless vector boson without mixing up to $O(\chi^2)$:

$$\begin{aligned} A_\mu & \rightarrow A_\mu - \chi A'_\mu \\ \mathcal{L} = & -\frac{1}{4}(F^{\mu\nu}F_{\mu\nu} + F'^{\mu\nu}F'_{\mu\nu}) - \frac{M^2}{2}A'_\mu A'^\mu \\ & - e\bar{\psi}\gamma^\mu\psi A_\mu - \chi e\bar{\psi}\gamma^\mu\psi A'_\mu + \dots. \end{aligned} \quad (2)$$

We see that the new massive vector boson, the dark photon, couples to the standard model charged fermions very weakly with an effective coupling constant χe . The value of the two

parameters, the mass M of the dark photon, and the coupling suppression factor χ are crucial to the phenomenologies of this new model.

Cosmic dark photons can be created from inflationary fluctuations. Inflation during the early universe addresses many theoretical puzzles and is therefore a very compelling model of the evolution of the universe [1, 2]. The inflationary fluctuation that produces dark photons [25] is purely gravitational and therefore only requires the dark photons to couple to the standard model sector particles weakly to avoid over production in hot plasma. The production mechanism is also attractive because the large scale isocurvature perturbations are suppressed so the power spectrum is dominated by adiabatic perturbations, which is consistent with current observations. The abundance of dark matter in this scenario is determined by the Hubble scale of inflation and the mass of dark photons:

$$\Omega_A/\Omega_{cdm} = [M^{1/2}/(6 * 10^{-6}\text{eV})] * [H_I/10^{14}\text{GeV}] \quad , \quad (3)$$

where H_I is the Hubble scale of inflation.

The cosmic dark photons are currently free streaming. Using the Lorenz gauge condition

$$\partial_\mu A'^\mu = 0 \quad , \quad (4)$$

then the field obeys the wave equation: $(\partial_\mu \partial^\mu + M^2)A'_\mu = 0$. As the cold dark matter particles are non-relativistic, in the momentum space we have:

$$A'_\mu(\vec{v}, t) \approx A'_\mu e^{i(-Mt - \frac{M}{2}v^2 t + M\vec{v} \cdot \vec{x})} \quad , \quad (5)$$

up to the second order of velocity v . From Eq.(4) and Eq.(5) we find that the time component of the vector field is suppressed by velocity v and is therefore small. For our subsequent discussions it is convenient to use the dark electric field \vec{E}' and dark magnetic field \vec{B}' instead of the vector field A'_μ . Because the spacial part of the vector field is much larger than the time part, we have $\vec{E}' = -\partial \vec{A}' / \partial t \approx -iM \vec{A}'$ and $\vec{B}' = \nabla \times \vec{A}' \approx 0$. We find that the vector dark matter is dark electric field dominant. The energy distribution is:

$$I_A = \frac{\rho_{cdm}}{\Delta E} \approx \frac{0.3\text{GeV}/\text{cm}^3}{(1/2)M\Delta v^2} \quad (6)$$

where $\Delta v \sim 10^{-3}c$ is the dark matter velocity distribution.

III. DESIGN OF THE EXPERIMENT

The hidden photon couples to fermions via:

$$\mathcal{L}_{\bar{\psi}\psi A'} = -\chi e \bar{\psi} \gamma^\mu \psi A'_\mu \quad , \quad (7)$$

where ψ is the electron field and χ is generally suppressed by loops in a more fundamental theory. The dark photons created from inflationary fluctuations have a mass of 10^{-5}eV if they are a major part of the dark matter. However, the creation mechanism itself puts little constraint on the coupling χ .

The Compton wavelength of the dark photon is $\lambda = 2\pi(M)^{-1}$. If we use the standard assumption that $m \sim 10^{-5}\text{eV}$, the respective wave length is much larger than the Bohr radius $a_0 \sim 10^{-10}\text{m}$ of atoms. Therefore the dark electric field can be treated as a homogeneous field in atoms:

$$|\vec{E}| = \sqrt{2\rho_{cdm}} \cos(Mt) \quad . \quad (8)$$

In the non-relativistic limit, Eq.(7) leads to the Hamiltonian:

$$H = -\chi e(\vec{E}' \cdot \vec{x}) - [\chi e/(4M)] \vec{\sigma} \cdot \vec{B}' + \dots \quad , \quad (9)$$

where σ is the Pauli matrices. We see that the first term is similar to the coupling of the electric dipole interaction and the second term plays the role of the magnetic momentum interaction. The second term is negligible because the dark magnetic field is very small. The dark dipole coupling of atoms cause $\Delta l = \pm 1$, $\Delta m = 0, \pm 1$ transitions if the energy gap between two states matches the energy of the dark photons, where l is the orbital angular momentum and m is the third component of angular momentum. The energy gap between two states can be adjusted by using the Zeeman effect with an external magnetic field \vec{B} . The general Hamiltonian of the Zeeman effect is $H = -\vec{\mu} \cdot \vec{B}$, where $\vec{\mu}$ is the magnetic moment of the electron. The mass range that can be scanned in a particular experiment is limited by the available magnetic field strength. Given today's technology, $B \sim 18\text{T}$, we have $\delta M \sim 240\text{GHz}$.

The transition rate R of atoms or ions from a initial state $|i\rangle$ to an excited state $|f\rangle$ is

$$R = \frac{4\pi\chi^2 e^2}{6} \frac{|\vec{E}'_0|^2}{\max(\Delta\omega_{A'}, \Delta\omega_{if}, \Delta\omega)} |\langle \vec{r}_{i,f} \rangle|^2 \quad , \quad (10)$$

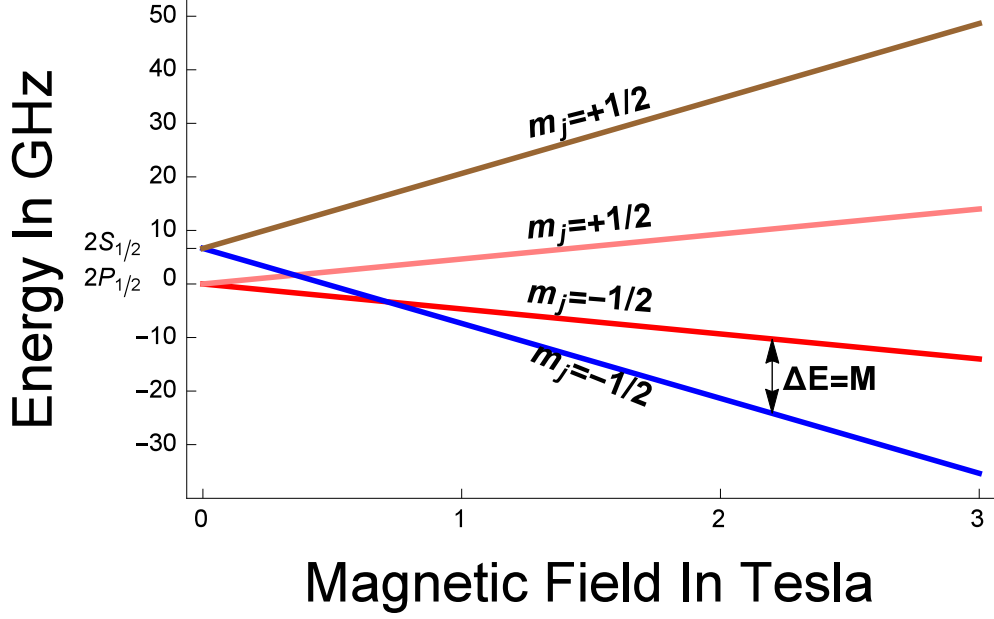


FIG. 1: The Zeeman effect on the 2s state and the 2p state. The energy gap between two states can be tuned using an external magnetic field. If the energy gap between two states matches the dark photon's mass, resonance transitions will occur. The mass range that can be scanned depends on the available magnetic field strength and the choice of target atoms or ions.

where $|\vec{r}_{i, f}|$ is the quantum matrix element between states $|i\rangle$ and $|f\rangle$, $\Delta\omega_{A'} = \frac{1}{2}M\Delta v^2$ is the bandwidth of cosmic dark photons, $\Delta\omega_{if} = 1/\tau$ is the bandwidth of the excited state, and $\Delta\omega = 1/\Delta t$ is the bandwidth of the useful integration time in a particular frequency range. The resonance condition is $M = E_f - E_i$ and E_i , E_f are the energies of the initial state and the final state, respectively. Because for the experiment, $\Delta\omega_{A'} \gg \Delta\omega \gg \Delta\omega_{if}$, we have:

$$R = \frac{4\pi\chi^2 e^2}{3} I_A |\vec{r}_{i, f}|^2, \quad (11)$$

where the I_A is defined by Eq.(6) which is the local dark photon energy spectrum distribution. The exact value of the matrix element of dipole transition $|\vec{r}_{i, f}|^2$ depends on the particular target material but we can estimate the order of magnitude in this preliminary assessment, which is considered a $2S \rightarrow 2P$ transition:

$$|\vec{r}_{i, f}|^2 \sim a_0^2. \quad (12)$$

The number of excited atoms or the number of events will be:

$$RNt = \frac{4\pi}{3}\chi^2 e^2 I_A a_0^2 Nt \quad , \quad (13)$$

where N is the number of populated $2S$ states and t is the integration time. These excited $2P$ atoms will decay rapidly into $1S$ atoms, and the emitted photons with a particular frequency can be registered as the number of events.

Because the electric dipole transition of $2S \rightarrow 1S$ is forbidden, the $2S$ state is semistable with a lifetime of about $1/7$ s, which is much larger than the lifetime, $2 * 10^{-11}$ s, of the $2P$ states. The $2S_{1/2}$ semistable states can be populated with electrons. Let us assume 10^{-2} mole/sec of the $2S$ state can be excited and stored, which takes the order of kW power, then the populated $2S$ states are about 10^{-3} mole at any given time.

IV. SENSITIVITY

The sensitivity of the experiment depends on the integration time and the efficiency of photon counting if the system is contained in a proper conductor shield that can annihilate the GHz electromagnetic field noise. A Faraday cage can serve as the shield, as it blocks radio frequency fields but has little interference with the dark matter photons and magnetic field generating the Zeeman effect. Let us assume a frequency bandwidth $\Delta B = M/(2\pi)$ is covered per working year for each experiment cycle. Then the magnetic field to induce the Zeeman effect is tuned so that the energy gap between two relative atomic states is shifting as:

$$\frac{\Delta B}{t_{cy}} = \frac{M/(2\pi)}{1 \text{ year}} = 77 \frac{\text{Hz}}{\text{sec}} \left(\frac{M}{10^{-5} \text{eV}} \right) \quad . \quad (14)$$

Because the band width of cosmic dark photons is $\Delta\omega_{A'} = (M\Delta v^2)/2$, during a cycle the event integration time is $t_{cy} * \Delta\omega_{A'}/\Delta B$.

During each cycle of the experiment, counted events can be checked by temporarily staying the frequency tune to see if additional events are registered. The number of events has a Poisson distribution so let us use η to denote the efficiency of the photon detector in counting an actual event. Therefore, to have a 95% confidence detection, the registered number of events satisfy $NRt > 3/\eta$. The sensitivity of the coupling χ is then:

$$\chi > \frac{3}{2|\vec{r}_{if}|e} \left(\frac{\Delta B}{\pi I_A N t_{cy} \Delta\omega_{A'} \eta} \right)^{1/2} \quad . \quad (15)$$

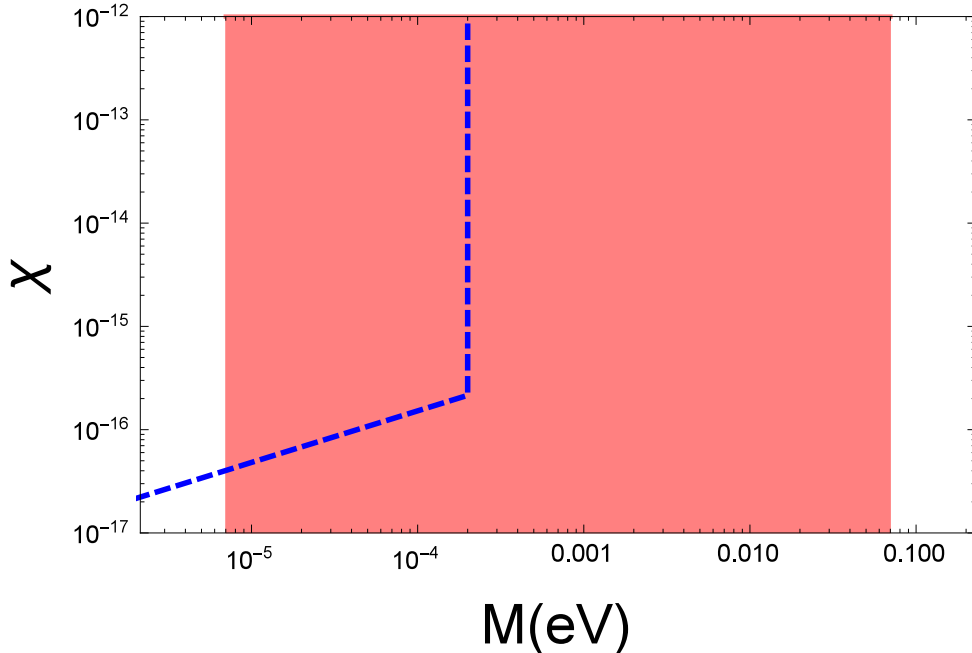


FIG. 2: Expected sensitivity of the experiment. The vertical pink band represents the possible mass range of the dark photon created by inflation fluctuations. The inflation production mechanism is completely gravitational and therefore does not have a theoretical constraint on the coupling of dark photons. The area above the blue dashed line is the sensitivity region for the preliminary set up of the experiment.

For a preliminary set up with 10^{-3} mole $2S_{1/2}$ atoms, one year cycle time, and detection efficiency $\eta \sim 0.6$, the sensitivity is $\chi \approx 4 * 10^{-17}$ for $M \approx 10^{-5}$ eV, see Figure. 2.

V. CONCLUSIONS

The hidden sector is a natural extension of the Standard Model of particle physics. Most models with a hidden sector include gauge groups that are independent from the known $U(1) \times SU_L(2) \times SU_C(3)$ standard model gauge groups. Therefore, hypothetical particles in the hidden sector interact very weakly with the standard model particles.

If the new $U(1)$ massive dark photons exist, they can be naturally produced by inflation. The production does not ruin the CMB power spectrum and appears inevitable. In addition, the production mechanism does not need a specified model because it is completely gravitational. Thus, the abundance of the production only depends on the Hubble scale of inflation

and the mass of the dark photon. Given the high energy scale of inflation $\gtrsim 10^{14}\text{GeV}$, and the rich ultraviolet structures of such a high energy scale, the uncertainty of the coupling is very high.

Experimental detections of these particles can serve as a probe to inflation. There are two practical problems in such an experiment: the first is that the coupling is very weak and the second is that the range of mass is very wide. Therefore, to cover the parameter space as much as possible, multi type experiments may be needed. In this paper, we propose the use of atomic transitions to detect the vector boson dark matter. The high energy spectral density of the vector boson dark matter will boost the transition rate of atoms if the energy gap between atomic states, which can be adjusted by the Zeeman effect, matches the mass of the dark photon. The excited states of the atoms can then be counted by registering the decaying photons. The reachable mass range of the experiment depends on the choice of target material and the available magnetic field for the Zeeman effect.

Acknowledgments: Q.Y. would like to thank Pierre Sikivie, Weitian Deng, Yungui Gong, Xiangsong Chen, Fen Zuo, Yunqi Liu, Bo Feng and Jianwei Cui for their helpful discussions. This work is partially supported by the Natural Science Foundation of China under grant Number 11305066.

-
- [1] A. H. Guth, Phys. Rev. D **23**, 347 (1981). doi:10.1103/PhysRevD.23.347
 - [2] A. D. Linde, Phys. Lett. B **108**, 389 (1982). doi:10.1016/0370-2693(82)91219-9
 - [3] J. Ipser, P. Sikivie, Phys. Rev. Lett. **50**, 925 (1983).
 - [4] J. Preskill, M. B. Wise, F. Wilczek, Phys. Lett. **B120**, 127-132 (1983)
 - [5] L. F. Abbott, P. Sikivie, Phys. Lett. **B120**, 133-136 (1983).
 - [6] M. Dine, W. Fischler, Phys. Lett. **B120**, 137-141 (1983).
 - [7] Z. G. Berezhiani and M. Y. Khlopov, Sov. J. Nucl. Phys. **52**, 60 (1990) [Yad. Fiz. **52**, 96 (1990)].
 - [8] L. H. Ford, Phys. Rev. D **35**, 2955 (1987). doi:10.1103/PhysRevD.35.2955
 - [9] D. H. Lyth and D. Roberts, Phys. Rev. D **57**, 7120 (1998) doi:10.1103/PhysRevD.57.7120 [hep-ph/9609441].
 - [10] M. Y. Khlopov, A. S. Sakharov and D. D. Sokoloff, Nucl. Phys. Proc. Suppl. **72**, 105 (1999).

- [11] P. Svrcek, E. Witten, JHEP **0606**, 051 (2006). [hep-th/0605206].
- [12] A. Arvanitaki, N. Craig, S. Dimopoulos, S. Dubovsky and J. March-Russell, Phys. Rev. D **81**, 075018 (2010) doi:10.1103/PhysRevD.81.075018 [arXiv:0909.5440 [hep-ph]].
- [13] A. Wagner *et al.* [ADMX Collaboration], Phys. Rev. Lett. **105**, 171801 (2010) doi:10.1103/PhysRevLett.105.171801 [arXiv:1007.3766 [hep-ex]].
- [14] H. Tam and Q. Yang, Phys. Lett. B **716**, 435 (2012) doi:10.1016/j.physletb.2012.08.050 [arXiv:1107.1712 [hep-ph]].
- [15] Hoskins *et al.* Phys. Rev. D **84**, 121302 (2011)
- [16] A. E. Nelson and J. Scholtz, Phys. Rev. D **84**, 103501 (2011) doi:10.1103/PhysRevD.84.103501 [arXiv:1105.2812 [hep-ph]].
- [17] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo and A. Ringwald, JCAP **1206**, 013 (2012) doi:10.1088/1475-7516/2012/06/013 [arXiv:1201.5902 [hep-ph]].
- [18] D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald, JCAP **1304**, 016 (2013) doi:10.1088/1475-7516/2013/04/016 [arXiv:1212.2970 [hep-ph]].
- [19] R. Essig, A. Manalaysay, J. Mardon, P. Sorensen and T. Volansky, Phys. Rev. Lett. **109**, 021301 (2012) doi:10.1103/PhysRevLett.109.021301 [arXiv:1206.2644 [astro-ph.CO]].
- [20] E. Aprile *et al.* [XENON100 Collaboration], Phys. Rev. Lett. **109**, 181301 (2012) doi:10.1103/PhysRevLett.109.181301 [arXiv:1207.5988 [astro-ph.CO]].
- [21] P. Sikivie, Phys. Rev. Lett. **113**, no. 20, 201301 (2014) doi:10.1103/PhysRevLett.113.201301 [arXiv:1409.2806 [hep-ph]].
- [22] R. Agnese *et al.* [SuperCDMS Collaboration], Phys. Rev. Lett. **112**, no. 24, 241302 (2014) doi:10.1103/PhysRevLett.112.241302 [arXiv:1402.7137 [hep-ex]].
- [23] Y. Hochberg, M. Pyle, Y. Zhao and K. M. Zurek, arXiv:1512.04533 [hep-ph].
- [24] S. Chaudhuri, P. W. Graham, K. Irwin, J. Mardon, S. Rajendran and Y. Zhao, Phys. Rev. D **92**, no. 7, 075012 (2015) doi:10.1103/PhysRevD.92.075012 [arXiv:1411.7382 [hep-ph]].
- [25] P. W. Graham, J. Mardon and S. Rajendran, Phys. Rev. D **93**, no. 10, 103520 (2016) doi:10.1103/PhysRevD.93.103520 [arXiv:1504.02102 [hep-ph]].
- [26] H. An, M. Pospelov, J. Pradler and A. Ritz, Phys. Lett. B **747**, 331 (2015) doi:10.1016/j.physletb.2015.06.018 [arXiv:1412.8378 [hep-ph]].
- [27] Y. Hochberg, T. Lin and K. M. Zurek, arXiv:1604.06800 [hep-ph].